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FINAL REPORT

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THE OFFICE OF NAVAL RESEARCH

from

THE UNIVERSITY OF CHICAGO

INSTITUTE FOR NUCLEAR STUDIES

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1. <u>Introduction</u>.

The idea of using as a thermometer the variation with temperature of isotopic fractionation factors in equilibrium reactions was first formulated by Urey (1) in 1947, in relation praticularly to the oxygen isotopes in the system CO_2-H_2O-$CaCO_3$.

In this system, the oxygen isotope fractionation factor between calcium carbonate and water is about 4%. greater at 0°C than at 25°C (1), which corresponds to a variation of 0.2‰ per degree centigrade.

Clearly, if the oxygen isotopic composition of water in which a given calcium carbonate has been precipitated is known or reasonably assumed, and if the chemistry involves exclusively equilibrium reactions, the temperature at which the precipitation occurred can be obtained by determining the oxygen isotopic composition of the calcium carbonate.

This idea appeared to open very wide possibilities of studying the past climatic history of the earth by measuring the oxygen isotopic composition of the calcium carbonate in well-preserved marine fossils. It was, therefore, aggressively pursued.

2. <u>The establishment of a technique</u>.

Since a precision of 1°C in the temperature determinations was considered desirable, mass spectrometers able to detect differences in oxygen isotopic abundances as small as 0.2‰ had to be developed. This meant multiplying by six the precision of the best instruments available at that time (2). The work was carried

out by McKinney, McCrea, Epstein and Allen, under the direction of Urey (3), and required more than a year. The new instrument was essentially a Nier-type mass spectrometer in which the intensity and stability of the ion-beam were increased, the output of the amplifiers was enlarged, the emission regulator was improved, and a system for the rapid, successive comparisons between two gas samples was introduced. With these modifications, the required sensitivity was obtained. The present precision of the instrument can best be evaluated by stating that the standard deviation of normal runs is 0.03 ‰.

At the same time, McCrea (4) recalculated the effect of temperature on the oxygen isotopic composition of calcium carbonate precipitated inorganically from aqueous solutions, and verified the results experimentally. The experimental part involved several problems which were successfully solved. Thus, the dissociation of calcium carbonate into calcium oxide and carbon dioxide had to be effected in such a way as to avoid introduction of erratic isotopic fractionation. Various methods, including both thermic and acid decomposition, were tested, and acid decomposition by means of 85% phosphoric acid with added phosphorous pentoxide was selected. Absence of oxygen isotopic exchange between this acid and the CO_2 produced in the decomposition was proved. Finally, inorganic calcium carbonate slowly precipitated from aqueous solution was proved to have the same oxygen isotopic composition as calcium carbonate precipitated by marine organisms at the same temperature (allowance being made for the different isotopic composition of the waters). This indicated absence of a "vital effect" on isotopic

fractionation processes, at least for the organisms considered, which were mostly molluscs. However, other organisms such as corals, echinoderms and oysters showed a possible "vital effect", tentatively correlated with intracellular symbiosis with Zooxanthellae algae. These organisms are less suitable or unsuitable for paleotemperature determinations. An alternate or additional explanation for the observed anomalies may be secondary deposition of calcite in the open-mesh wall structure of the organisms in question. A large number of marine organisms remains available, and the research was focussed on these.

Before routine analyses of fossil material could be undertaken, it was necessary to establish an empirical temperature scale based on analyses of calcium carbonates organically deposited at different temperatures and referred to an arbitrary standard. This was necessary because the theoretical temperature effects were only approximate. However, it soon became apparent that the simple acid decomposition used by McCrea on inorganic calcium carbonate could not be applied to calcium carbonate organically precipitated. If this was done, the CO_2 obtained appeared to contain variable amounts of organic impurities of masses identical with or close to the masses to be measured.

The work of eliminating these impurities and establishing the empirical temperature scale was done by Epstein, with the constant advice of Urey (5). The method first adopted for eliminating the organic impurities involved heating the powdered calcium carbonate at 400°C in a stream of helium purified through a furnace containing copper oxide. This treatment lowered the O^{18} content in the CO_2,

but made the results much more consistent. Thirteen shells grown at various temperature levels between 7.4 and 29.0°C were analyzed and an equation between temperature and mass spectrometric data was based on the results (5).

Soon afterwards, however, it was realized that a constant error was being introduced. After much experimentation, the error was traced to passage of small amounts of oxygen from the copper oxide in the furnace to the helium stream, and this was eliminated by substituting copper for copper oxide in the furnace, by adding a charcoal trap, and by raising to 475°C the temperature of the powdered calcium carbonate.

A new equation between temperature and mass spectrometric data was obtained from samples processed with the new technique (6). This is:

$$t = 16.5 - 4.3(\delta - A) + 0.14(\delta - A)^2$$

where δ is the permil difference between the ratio of masses 46 and 44 in the sample and the standard gas, and A is the difference between the δ value of a CO_2 gas equilibrated with the water in which the organic calcium carbonate had been precipitated and the δ value of a CO_2 gas equilibrated with average marine water.

3. <u>Some general considerations.</u>

Before applying the method to problems of geological interest, some important questions must be discussed.

The temperature equation given above shows that a unique solution is obtained only if the isotopic composition of the water in which a given calcium carbonate has been precipitated is also known. Epstein et al. (5) and Epstein and Mayeda (7) investigated the variability of the oxygen isotopic composition of marine waters. It was found that, since the molecule H_2O^{16} has a greater vapour pressure than the molecule H_2O^{18}, there is a general depletion of O^{16} of about 1‰ in the two tropical evaporation belts, and corresponding enrichment in the higher latitudes. If marginal environments are taken into consideration, variation as large as 8-10‰ induced by excessive evaporation or influx of fresh waters may be observed.

The uncertainty so introduced in the paleotemperature measurements of fossil material can be eliminated only be establishing another temperature equation for a different oxygen isotope exchange reaction: the simultaneous solution of both equations for the two unknowns δ and A would give a unique temperature value.

The best chance appeared to be the possible exchange reaction between calcium phosphate and water. Work along these lines was started in 1949 by Steinberg, was followed up by Craig, and is now being pursued by Tudge. Although no effort was spared, it has not yet been possible to extract the oxygen from the phosphate ion without introducing some erratic isotopic fractionation. The latest work, however, indicates that success is now near.

Another problem involves possible post-depositional exchange between the calcium carbonate of buried organisms and percolating waters. Apart from obviously recrystallized remains which may

contain nothing of the original material, oxygen diffusion through solid matter may have affected otherwise well preserved fossils. Estimates by Urey (2) showed that diffusion through rather coarse crystals may occur in a time as short as 1 million years, if the proper temperature obtains, while in very small crystals it may occur in a few thousand years. However, an Upper Jurassic belemnite from the Island of Skye, west of Scotland, showed very convincingly that no diffusion had taken place in 150 million years since the record of the temperature seasonal variations were not erased. Moreover, thin shells of benthonic foraminifera of Oligocene age from the deep waters of the eastern equatorial Pacific gave δ values of about 1.5 (8), corresponding to a temperature of 10.4°C, although they had remained in contact with much colder waters for at least 20 million years.

The present impossibility of solving the temperature equation for both δ and A at the same time imposes some limitations on the choice of the material to be run and requires the introduction of some assumption. Thus, it must be assumed that the oxygen isotopic composition of marine waters did not change through geologic time. This is probably true, at least since the beginning of the Mesozoic and perhaps much earlier. In fact, although the sediments tend to subtract O^{18} from the sea, their recycling may have reduced this effect to a minimum since probably the Cambrian.

Although a greater oxygen isotopic uniformity of the sea water is envisaged in non-glacial times (7), it is advisable at present to avoid using fossils indicating marginal environments, where the water may have had an abnormal isotopic composition. In addition,

an approximate correction of +1% for the two tropical bands and of -1% for the high latitudes may be applied to correct the major oxygen isotopic variation of the sea water with latitude.

4. <u>The relation between natural temperatures and temperatures determined by means of oxygen isotopic analyses.</u>

Paleotemperature data must be subject to careful interpretation, because the inference of the environmental temperature and its seasonal variation from the temperature at which a given calcareous organism deposited its calcium carbonate may not be easy or direct. A number of biological and ecological factors must be taken into consideration. Among these the most important are the temperature ranges of calcium carbonate deposition and the depth habitats of both pelagic and benthonic organisms.

To investigate temperature ranges of calcium carbonate deposition, Epstein and Lowenstam (9) analyzed a large number of marine shells from Bermuda. Two methods of analysis were employed: average shell samples were run, thus obtaining "weighted" temperature averages of skeletal deposition; or successive increments of shell material were analyzed, thus obtaining the different temperatures at which different parts of the shells were deposited.

The temperature of the marine superficial waters in Bermuda varies during the year from 17 to 28°C. The "weighted" average temperature values varied between 18.1 ± 0.5°C and 29.3 ± 0.5°C. This range was obtained from an array of 54 temperature values, and it checks very well with the natural temperature range. It

should be observed that little information could have been obtained from a single temperature determination, while a large number of measurements gave a very good idea of the natural temperatures. The same result was obtained by a continuous series of 84 samples from a single shell of Strombus gigas: a temperature range from 17.2 ± 0.5°C to 27.0 ± 0.5°C was obtained.

Both methods would of course fail at extreme temperatures, that is, at temperatures too low or too high for shell growth. The first case is particularly important, as the seasonal minimum may often be several degrees lower than the threshold of shell growth of many species, particularly in the middle and high latitudes. In these cases, only the seasonal maximum may be determinable, but this will constitute in itself a very valuable piece of information.

More recently, Emiliani has developed a more rapid method of determining temperature ranges from molluscs by sampling the shells in a discontinuous way (Fig. 1). With this method, it is usually possible to determine temperature ranges with 20-30 analyses instead of the 50-80 previously necessary. Recent work done with molluscs from Bermuda shows that the temperature ranges obtained compare very well with the known ones, represented by the thick lines along the temperature scales (Fig. 2).

5. Mesozoic temperature measurements.

For the first major application to the fossil of the oxygen isotopic method of temperature determination, Upper Cretaceous

material was selected (10). This choice was advised by the special climatic interest that this period of the history of the earth has and by the availability of such fossils as belemnites, which gave best assurances against post-depositional alterations.

Belemnites, brachiopods and oysters from the Cenomanian-Senonian of England, and belemnites from the Maestrichtian of Denmark and the southeastern United States were analyzed with the method of running an average sample of calcium carbonate from each specimen.

The results (Table 1) show that the temperature ranges obtained from the three areas are rather similar, and markedly different from today's, in agreement with the views of the geologists on the subject.

Table 1

Temperature ranges obtained from average samples of calcium carbonate from Upper Cretaceous belemnites

Location	Age	No. of Spec.	Temperature ranges (°C) Fossil.	Now
Denmark	Maestrichtian	3	13.3 - 15.3	3 - 16
England	Senonian	5	15.4 - 23.8	7 - 18
S.E. United States	Maestrichtian	39	12.9 - 21.6	20 - 27

These results, which were considered preliminary, were published in 1951 (10). Subsequently, a large quantity of fossils of Upper Cretaceous age was collected in Europe, North Africa and North America by Lowenstam (11). The collection included mainly belemnites, molluscs, brachiopods, and a number of samples of associated chalks. The fossils were largely run with the method, previously mentioned, of analyzing average samples of calcium carbonate from each specimen. Almost all of the belemnites appeared to have preserved the original isotopic composition. On the other hand, most of the chalks, brachiopods and molluscs, except a series of nine Inoceramus from the Upper Campanian of Norfolk, England, and a few others, showed enrichment in O^{16}. This was thought to have been produced mainly by addition of secondary calcite during the fossilization process.

A large number of stratigraphic levels from the regions above mentioned were considered, from which one or more specimens of belemnites were examined. Although the number of specimens per level was never large enough to allow accurate determinations of temperature ranges, a very clear trend of increasing temperatures was discovered from the Cenomanian to the Santonian, and of decreasing temperatures from the Santonian to the Maestrichtian. Moreover, it was confirmed that the Maestrichtian temperatures in northern Europe and the southeastern United States were remarkably similar, and it was shown that the yearly temperature range in the Upper Cretaceous as a whole could not have much exceeded 6°C, at least in most cases. This, in fact, is the range shown by 34 specimens of belemnites from the Swedish Lower

Campanian, by 40 specimens from the English Upper Campanian, and by 44 specimens from the American Maestrichtian.

The continuous samples concentrically ground from the previously mentioned Upper Jurassic belemnite from the island of Skye showed a temperature range from 18.5 to 22.7°C. Another belemnite from the Upper Jurassic Oxford Clay of Northamptonshire, England, and a specimen from the Upper Jurassic of New Zealand were subsequently analyzed with the same system. The temperature ranges were respectively 15.9 to 24.0°C and 11.3 to 25.4°C. Further researches along these lines are in process, with the main purpose of determining the major climatic zones during the Mesozoic and adding information to the problem of possible large, relative movements of the continental masses during this time. There is little doubt that the aims of this project, which is of paramount interest to the geological sciences, will be successfully achieved if sufficient financial support can be secured to carry out the thousands of analyses which are necessary.

6. Some problems of biological interest.

The analyses of continuous, concentrically ground samples from belemnites and molluscs also throw light on the life span of these animals. Thus, the Upper Jurassic belemnite from the island of Skye clearly lived three and a half years and died in the Spring (10, pl. 1, fig. 2). The other two Upper Jurassic belemnites (from England and New Zealand) show somewhat shorter life spans. Life spans of two to four years were also determined for mulluscs from Bermuda (9).

Similar studies on paleontologically young and old populations of the same species are scheduled. These will serve to further elucidate the mechanism of growth, decline, and extinction of specific populations, and will have broad interest for the biologist, the paleontologist, and the student of evolution. Again, a great many analyses will be necessary before it will be possible to outline a consistent picture of the complex biological phenomena involved. Belemnites will constitute excellent material for this project also.

7. <u>The study of the Pleistocene climate.</u>

Epstein and Lowenstam left the University of Chicago for the California Institute of Technology in the summer of 1952. They were succeeded by Emiliani and Edwards, with Emiliani in charge of the paleotemperature project and Edwards in charge of the upkeep of the mass spectrometers.

Emiliani joined the group a year and a half before Epstein and Lowenstam left. During this time, he first helped with the problem of removing the organic material from the samples, and then started a project of his own directed to the study of the Pleistocene climate. A first study involving 65 samples of calcarenite from the Lower Pleistocene Lomita Marl of southern California was completed in 1952, in collaboration with Epstein (12). The samples were collected in stratigraphic order, at a distance of 1/2 foot, and from each sample three groups of benthonic foraminifera, Miliolidae, <u>Elphidium</u> spp. and <u>Cassidulina</u> spp., were separated. Each group from each sample was then run

separately. Three rather complicated but perfectly corresponding temperature curves were obtained, with temperatures ranging from 12 to 30°C (12, Fig. 2). From the fact that both Elphidium and Cassidulina gave temperatures consistently lower than the Miliolidae, it was deduced that submarine solifluction had occurred throughout as a continuous phenomenon.

A more detailed study of this pheonmenon and of the larger scale turbidity currents has been scheduled, based on oxygen isotopic analyses of tests of benthonic foraminifera from the continental shelf and slope. Clearly, if foraminiferal shells from the same samples show different temperatures, as in the Lomita Marl samples, a downslope movement of the sediments will be indicated.

Analogous criteria have been applied to the study of tectonic, isostatic and enstatic movements. Benthonic foraminifera 12,000 years old (radiocarbon age determination) from the top of a North Atlantic sea-mount now 366 m. deep gave a temperature of 16.8°C. This shows that 12,000 years ago, when the top of this sea-mount stood near the sea surface, the temperature of the superficial sea waters was lower than today's (22°C). More studies of this type are scheduled, in collaboration with Dr. B. Heezen, of the Lamont Geological Observatory of Columbia University, and Dr. E. L. Hamilton, of the U. S. Navy Electronics Laboratory at San Diego, California.

The depositional depth of geological formations can be estimated rather accurately by measuring the difference between the temperatures given by pelagic and benthonic foraminifera. This

criterion will be applied to investigation of the depositional depth of the Miocene Donni formations of Saipan, in collaboration with the U. S. National Museum.

The largest amount of research on paleotemperatures underway at present, however, deals with deep-sea cores. A very large number of these cores, more than a thousand, has been collected during the post-war years in the course of various expeditions. Of particular importance are the collections assembled by the Oceanografiska Institutet of Göteborg, Sweden, the Lamont Geological Observatory of Columbia University, and the Scripps Institution of Oceanography. The recent emphasis on submarine coring is in good part due to the development of the piston corer by Kullenberg, which permits the raising of cores up to 20 m. in length.

Submarine cores of suitable length and from suitable areas may contain a continuous geological record which may encompass the whole of the Pleistocene and may, in some cases, continue downward well into the Pliocene. Many of these cores are formed by <u>Globigerina</u>-ooze throughout and, therefore, contain a very large number of specimens of various species of pelagic foraminifera. Temperature analyses of closely spaced samples of pelagic foraminifera from a number of cores from various parts of the world will permit the reconstruction of the Pleistocene climate with great accuracy, and will help solve a number of problems of very great interest to students of various disciplines.

Before proceeding to mass analyses of pelagic foraminiferal tests from the deep-sea cores, it was thought necessary to investigate the depth habitats of the different species, as there was some evidence that different species may live at different depths and, therefore, may register different temperatures.

A number of analyses of modern material from the Atlantic and Pacific Oceans and the Gulf of Mexico showed that different species do actually live at different depths (13). It was also shown that the stratification of the specific populations was the same in the three areas, and that the controlling factor was the density of the sea water.

From this it follows that in the investigations of the cores it is necessary to analyze tests of the same species throughout, and it is convenient to use species like *Globigerinoides rubra* and *Globigerinoides sacculifera* which live very close to the surface of the sea and will, therefore, more easily register whatever temperature variations may occur immediately above.

So far, five deep-sea cores have been analyzed. Of these, three are from the eastern equatorial Pacific, one from the Caribbean and one from the Mediterranean. The three Pacific cores had been studied in great detail by Arrhenius, together with numerous other cores from the same area (14). Arrhenius proposed 9 colder and 9 warmer Pleistocene stages, on geochemical and micropaleontological evidence. The oxygen isotopic analyses on the best sampled core (Fig. 3) indicated that actually the major colder periods were four. The temperature variations were

of the order of only 2 - 4°C, but they refer to a depth of about 130 m., that is the depth habitat of the species Globorotalia tumida, which was used for the analyses in the absence of more suitable, shallower species. The temperature variations at the surface were certainly larger. It was also shown that the Pliocene, which was entered by one of the cores, had temperatures about 1°C warmer than today's. More samples from this core are being run at present, so as to cover in greater detail the curve shown in Fig. 3.

In the Caribbean core a more suitable species, Globigerinoides sacculifera, was available throughout. The four glacial stages, preceded by a possible fifth one, and the four interglacial stages were beautifully revealed (Fig. 4). The temperature variation was found to be of the order of 8°C but, if correction for the enrichment in O^{18} of the marine waters during the glacial stages is made, the temperature of the colder stages would increase by about 2°C and the amplitude of the thermic oscillations would be reduced correspondingly. If the rates of sedimentation were roughly constant, it would appear, as may be seen from Fig. 4, that 1) the Wisconsin was twice as long as the other glacial stages; 2) the so-called "Great Interglacial" was not longer than the other interglacial stages; and 3) the process of warming up and also, to a smaller extent, the process of cooling were very swift. All three points seem to be supported by the Pacific core shown in Fig. 3, although its sampling is still too coarse. These points will be clarified when data become available from

additional cores, including another, longer core from the Caribbean and a core from the equatorial Atlantic. The third point, however, may already be considered as a proven fact because it is very hard to imagine how increasing and decreasing temperatures should correspond always to greatly reduced rates of sedimentation. Other important points shown by the curves of Fig. 4 are that 1) important temperature variations occurred also in tropical and equatorial areas during the Pleistocene; and 2) there is no apparent correlation with the Milankovitch curve of varying solar radiation which, for these latitudes, consists of a rather regular series of peaks and valleys of similar amplitudes with a period of about 21,000 years.

Of great interest also will be the results from core R10-10, raised from the bottom of the North Atlantic by Dr. Ewing, of the Lamont Geological Observatory. This core, although largely exempt from terrigenous sediments, has an unusually high rate of sedimentation, and a level 80 cm. below the top was dated as 5000 years old by Kulp using the radiocarbon method (15). It will be possible, therefore, to study in great detail the temperature variations in prehistoric and historic times.

The Mediterranean core (Fig. 5) has revealed very wide (7 to 31°C) and abrupt temperature variations. Unfortunately, the top part of this core is missing and, therefore, it is not known which part of the Pleistocene is covered. Radiocarbon age determinations are being made by Dr. Hans Suess on selected levels of this core and will probably clear the stratigraphic relationship.

Although the amplitude of the temperature variation in this core may have been exaggerated by influx of melt water during the cataglacial phases and by excessive evaporation during the anaglacial phases, much of the paleontological evidence from the Mediterranean area appears to lend support to our data. For instance, in the famed "Grotta Romanelli", a cave in the south-eastern tip of Italy, a closely alternated sequence of typically tropical and typically subarctic faunas exist. A corresponding variation of the nearby sea waters of some 20 - 25°C does not seem at all improbable. However, more cores from the Mediterranean need to be analyzed before an organic picture of the Pleistocene climatic evolution of this area will emerge.

The temperature variations in the Mediterranean core are not so wide as to make one suspicious that large quantities of melt water entered the Mediterranean. Against this fact there is also the occurrence throughout of abundant, apparently flourishing faunas of foraminifera. On the other hand, estimates of the amount of melt water which should have drained into the Mediterranean during the cataglacial phases from southern, central and eastern Europe and from western Siberia lead to a figure which is not far from the total amount of water now present in the Mediterranean. Clearly, such an enormous amount of fresh water could not have invaded the Mediterranean even once without killing all its foraminiferal faunas and very deeply altering its isotopic composition. It seems that we have here further indication that a good part, if not most, of the Pleistocene ice disappeared by evaporation rather than by melting.

The abruptness and the magnitude of the Pleistocene temperature variations invites the scientist to speculate as to the immediate causes. Obviously, long and slow phenomena such as mountain building cannot be held responsible. Also, as previously mentioned, the variation of the solar radiation on different parts of the Earth, because of the complex earth movements, does not appear to bear directly on the problem. The theory that requires the earth to enter and leave periodically a cloud of cosmic dust has been subjected to some tests by Emiliani, who calculated variation with depth of the Ni/Fe and the Ni/Ti ratios in central Pacific cores from data presented by Landergren (16). The results, however, were rather erratic and not consistent with the theory. At present the best hypothesis may well be the one based on changes of the solar constant, with sudden flares which rapidly increased the rates of evaporation of terrestrial waters.

8. Pleistocene raised beaches.

A very convenient material which can be utilized for the study of the Pleistocene climate at certain times are the mollusc shells which occur on many raised beaches. These beaches represent synchronous world-wide time-levels of higher sea, and offer a good opportunity of comparing climate on a world-wide basis. Emiliani spent part of the summer of 1952 collecting material of this type in France, Spain, Portugal, Morocco, and Italy. The shells are analyzed with the system of discontinuous sampling previously mentioned, with the purpose of determining temperature ranges and, in particular, temperature maxima. This,

again, is a long project, but some local studies have already been completed. As an example, the results obtained with Recent and fossil populations of the two mollusc species Conus mediterraneus and Columbella scripta from Kouali Point, Algeria, are presented (Fig. 6). The fossil specimens were collected from a raised beach belonging to the 2 m. level (17), and the temperature maximum obtained with this material was about 2°C lower than the one obtained with Recent material.

9. Long range temperature fluctuations.

It has been mentioned before that one of the Pacific cores entered the Pliocene. Two more cores from the same area entered directly into the Tertiary, the younger sediments having been removed by submarine erosion or slumping (14). The Tertiary sediments were dated by Emiliani on micropaleontological bases as Middle Oligocene and Lower-Middle Miocene. From these and from the Pliocene sediments previously mentioned, benthonic foraminifera were isolated. The temperatures obtained were 10.4°C for the Middle Oligocene, 7.0 for the Lower-Middle Miocene, and 2.2°C for the Uppermost Pliocene, while today's temperature is 1.7°C (18). Since regional subsidence or a general rise of the sea level may be excluded (18), a decrease of about 8°C in the temperature of the deep-sea waters of the Pacific may be considered as proved. This adds to the evidence already available indicating a general decrease of the temperature during the Tertiary (19). Furthermore, as the bottom temperatures of the deep, open Pacific basins are conditioned by the temperatures of the superficial waters in the polar seas, the Tertiary

temperatures above mentioned are indicative of the coeval polar temperatures.

If this information is combined with the information about the Uppor Cretaceous climatic trend, a highly generalized picture is obtained of increasing temperature from the early to the middle Upper Cretaceous and of decreasing temperature from the middle Upper Cretaceous to the Upper Pliocene. It is our intention, on the one hand, to extend paleotemperature measurements back in time as far as unaltered fossils can be encountered, and, on the other hand, to integrate with many more data the scarce evidence for the Tertiary, so as to see how close to reality is the generalized picture of climatic evolution which has been presented here.

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ADDENDUM

After this report had been written, radiocarbon measurements were made by Dr. Hans Suess on two samples from the Caribbean core and two from the Mediterranean core. The results from the Caribbean core, given below, show that the Wisconsin began a little earlier than 35,000 - 40,000 years ago in agreement with age determination on land material, and indeed about 16,000 years ago in the area under consideration. Their data show also that the rate of sedimentation during the Wisconsin was considerably higher than in postglacial times. The results from the Mediterranean core show that the top of the core is missing, as indicated also by the temperature graph.

Core	Cm. below top of core	Age (years)
Caribbean	30-34	15,700
"	148-152	35-40,000
Mediterranean	10-20	17,240
" "	170-180	>40,000

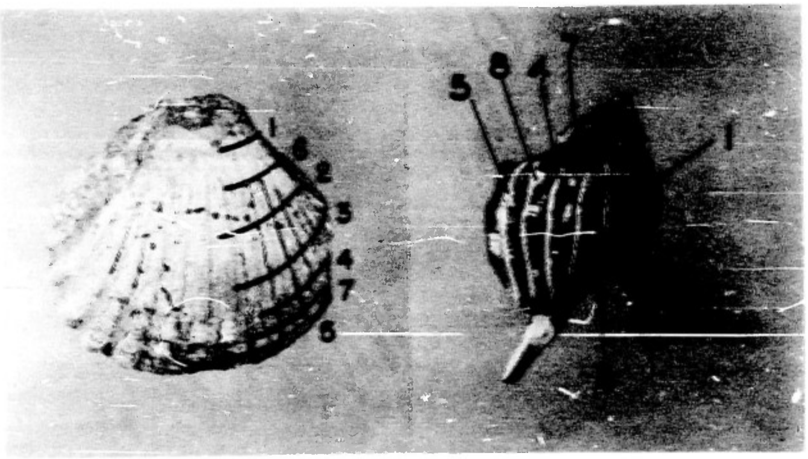


Fig. 1

Spot sampling of mollusc shells. The numbers indicate the order of sampling.

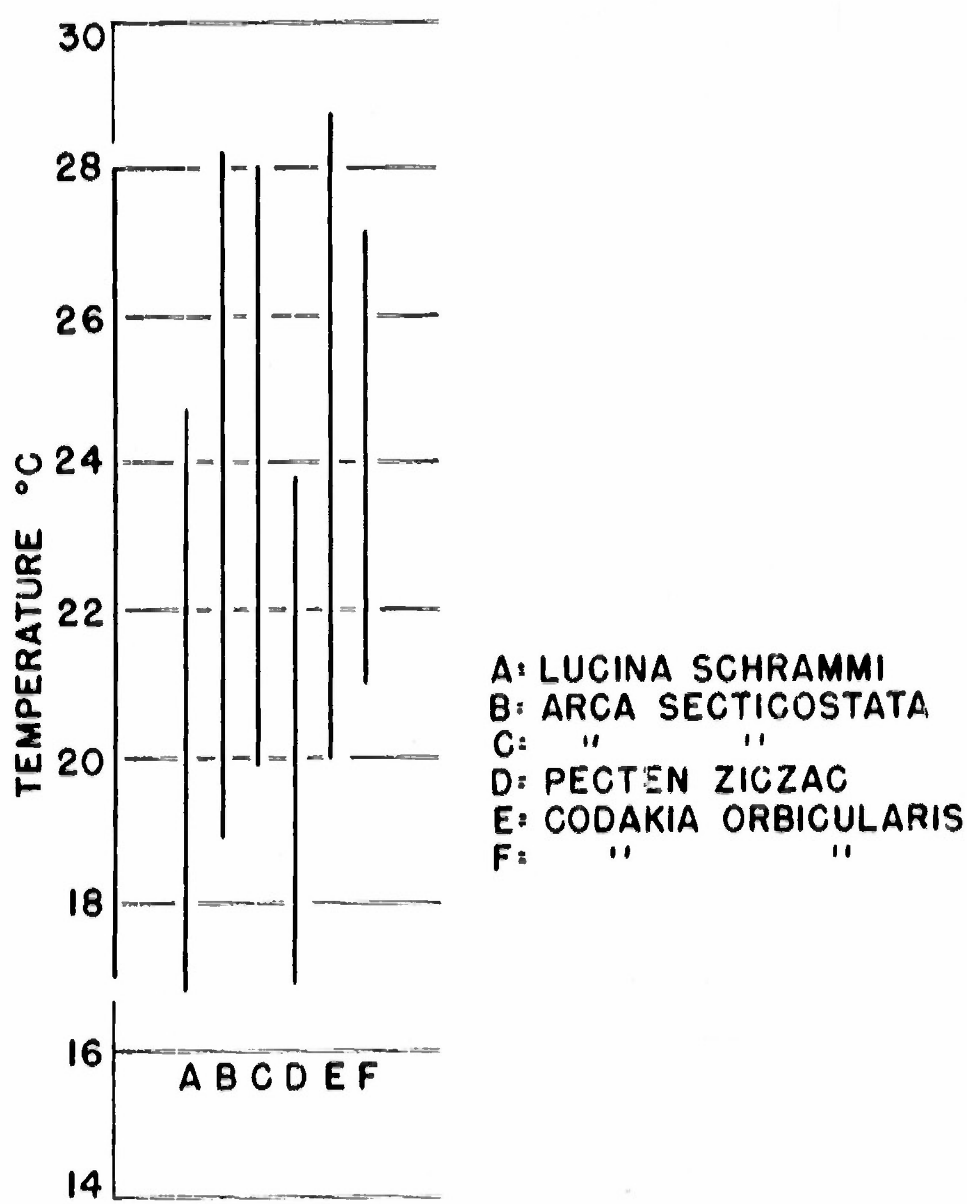
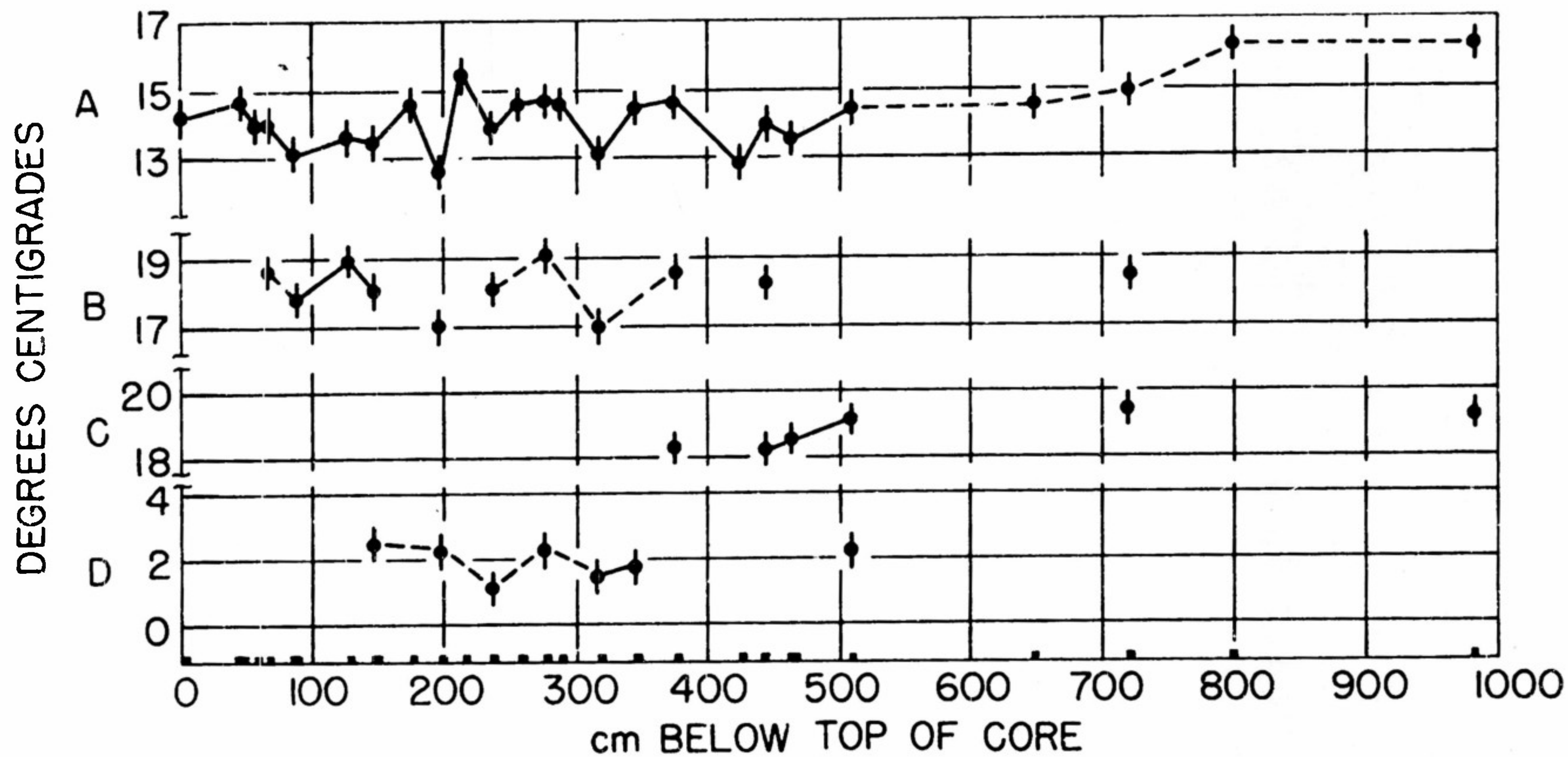


Fig. 2

Temperature ranges obtained from six molluscs from Bermuda. The thick line along the temperature scale represents the environmental temperature range.



A: GLOBOROTALIA TUMIDA
B: PULLENIATINA OBLIQUILOCULATA
C: SPHAEROIDINA DEHISCENS
D: BENTHONIC FORAMINIFERA

Fig. 3

Core 58 of the Swedish Deep-Sea Expedition: eastern equatorial Pacific. Temperature values obtained from different species of pelagic foraminifera, with included some values from benthonic foraminifera. The species Globorotalia tumida is the most abundant and gives the most continuous temperature record.

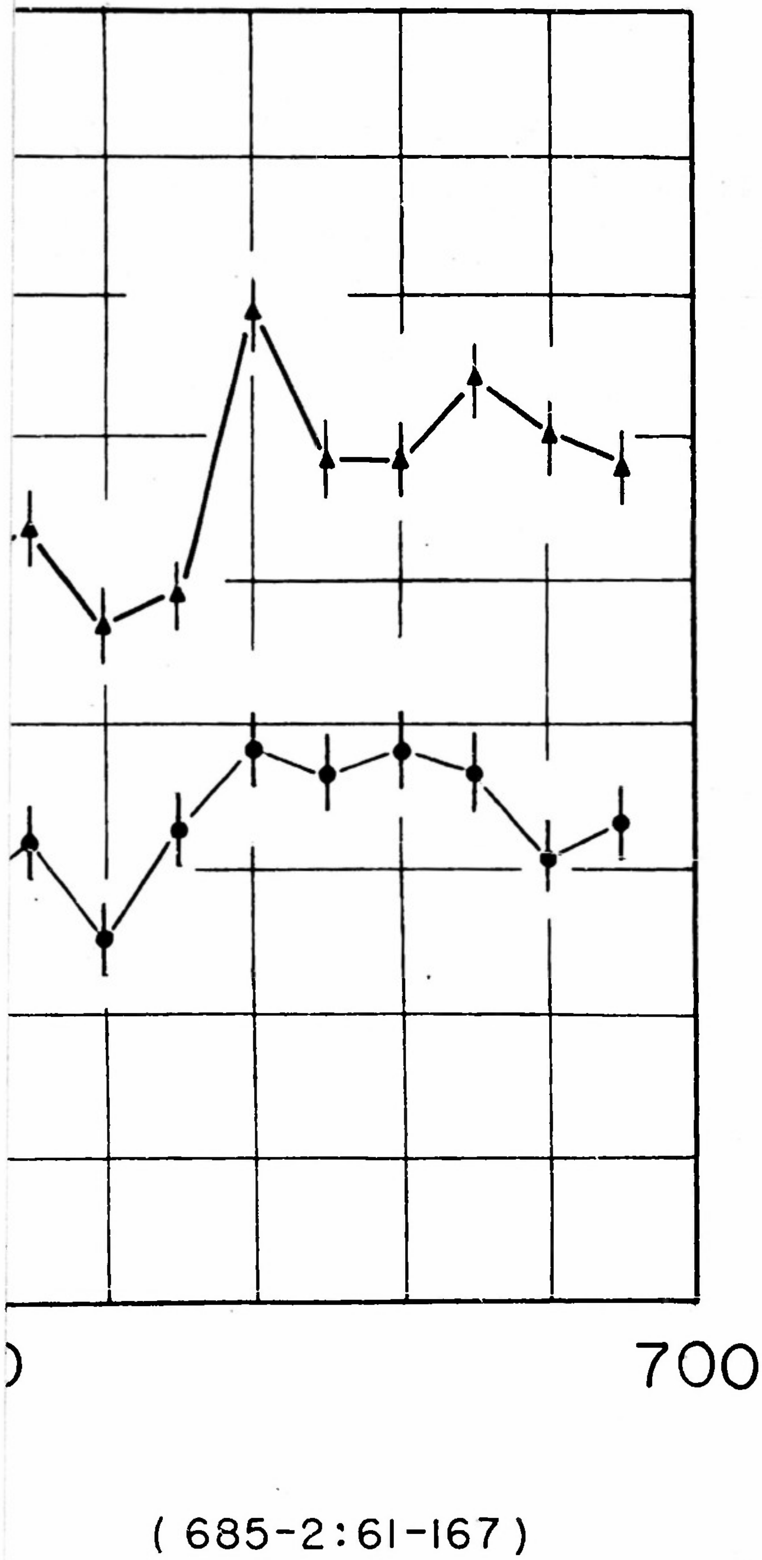
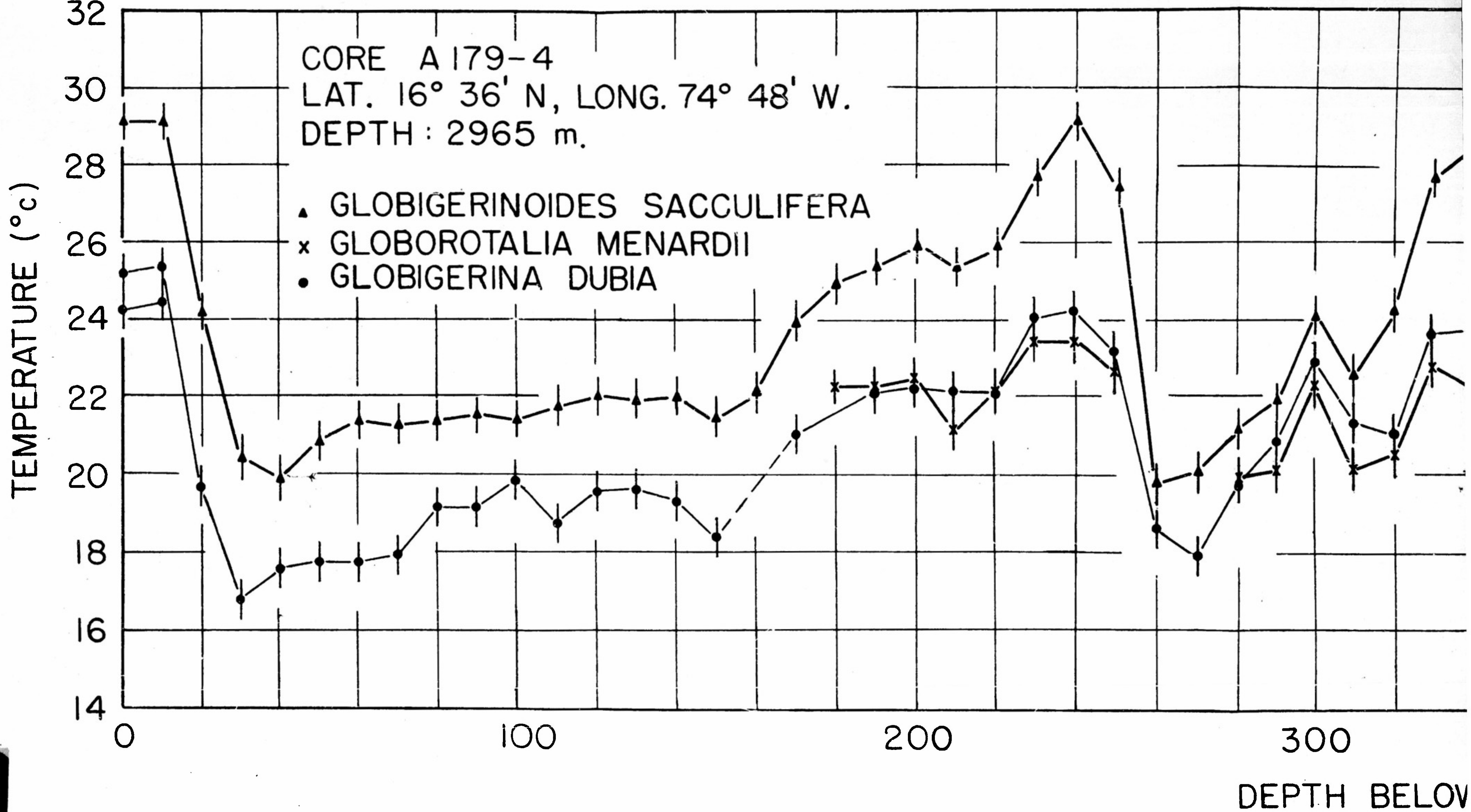
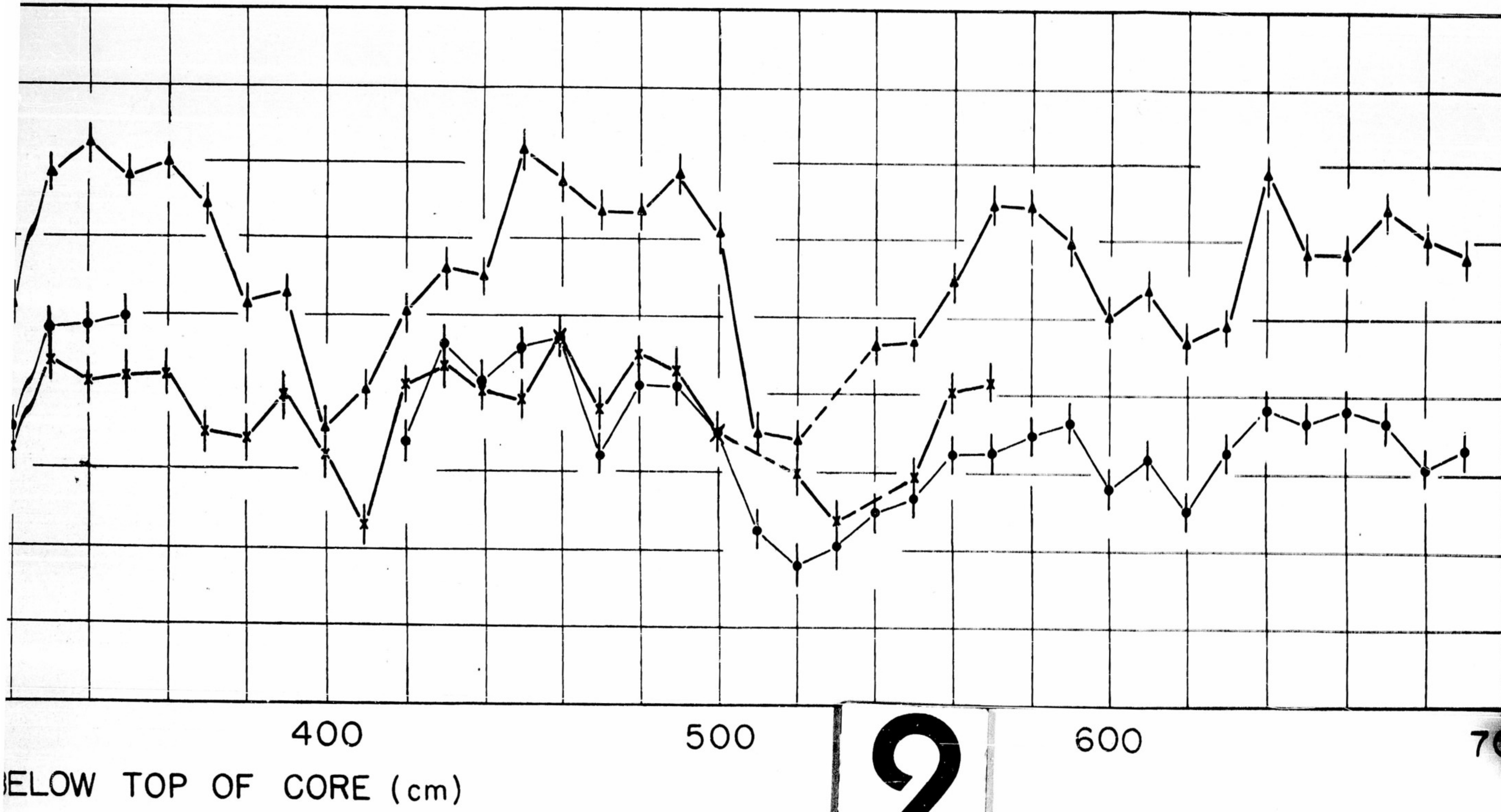


Fig. 4: Caribbean core.



1

Fig. 4: Caribbean core.

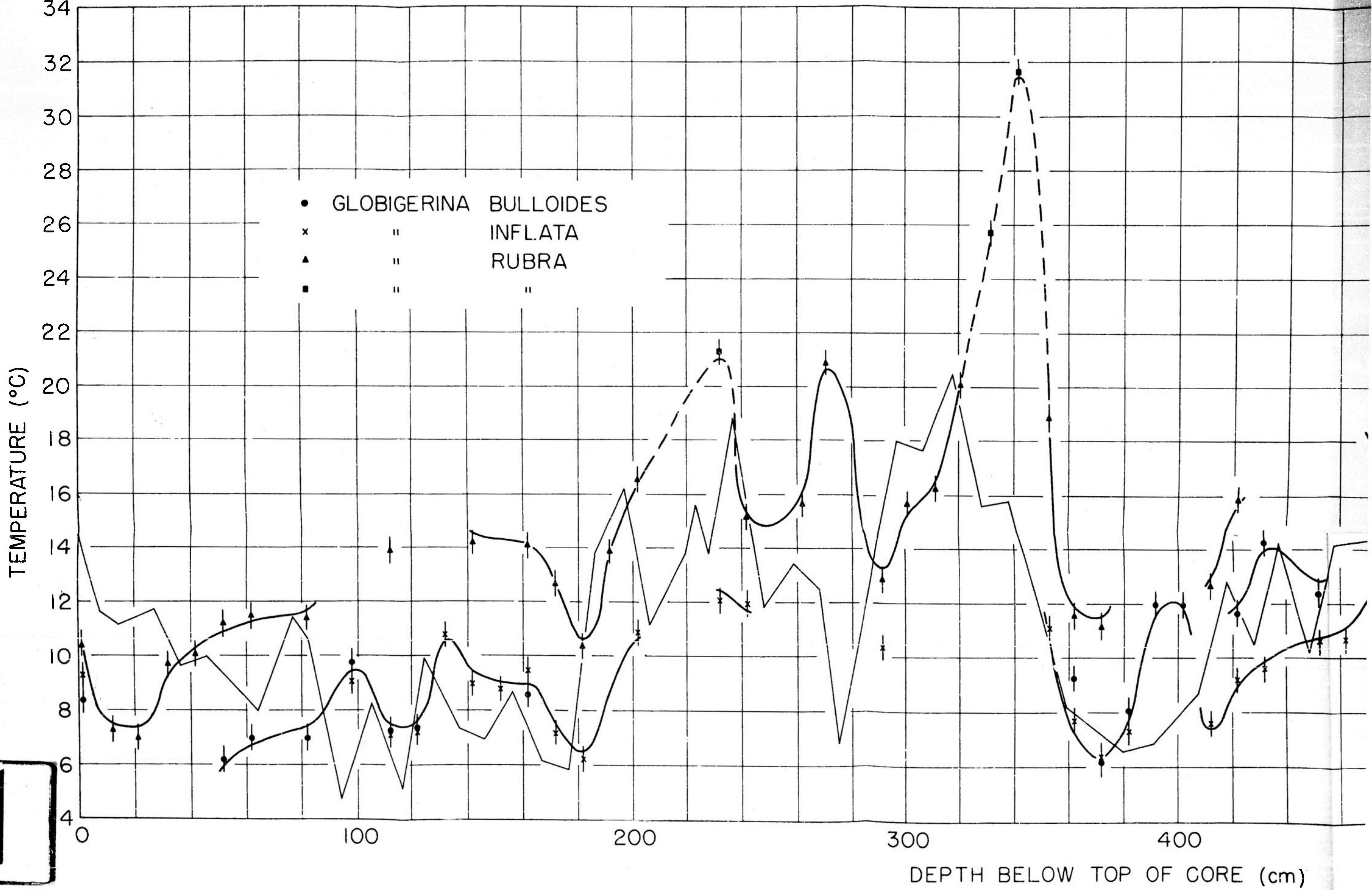


2

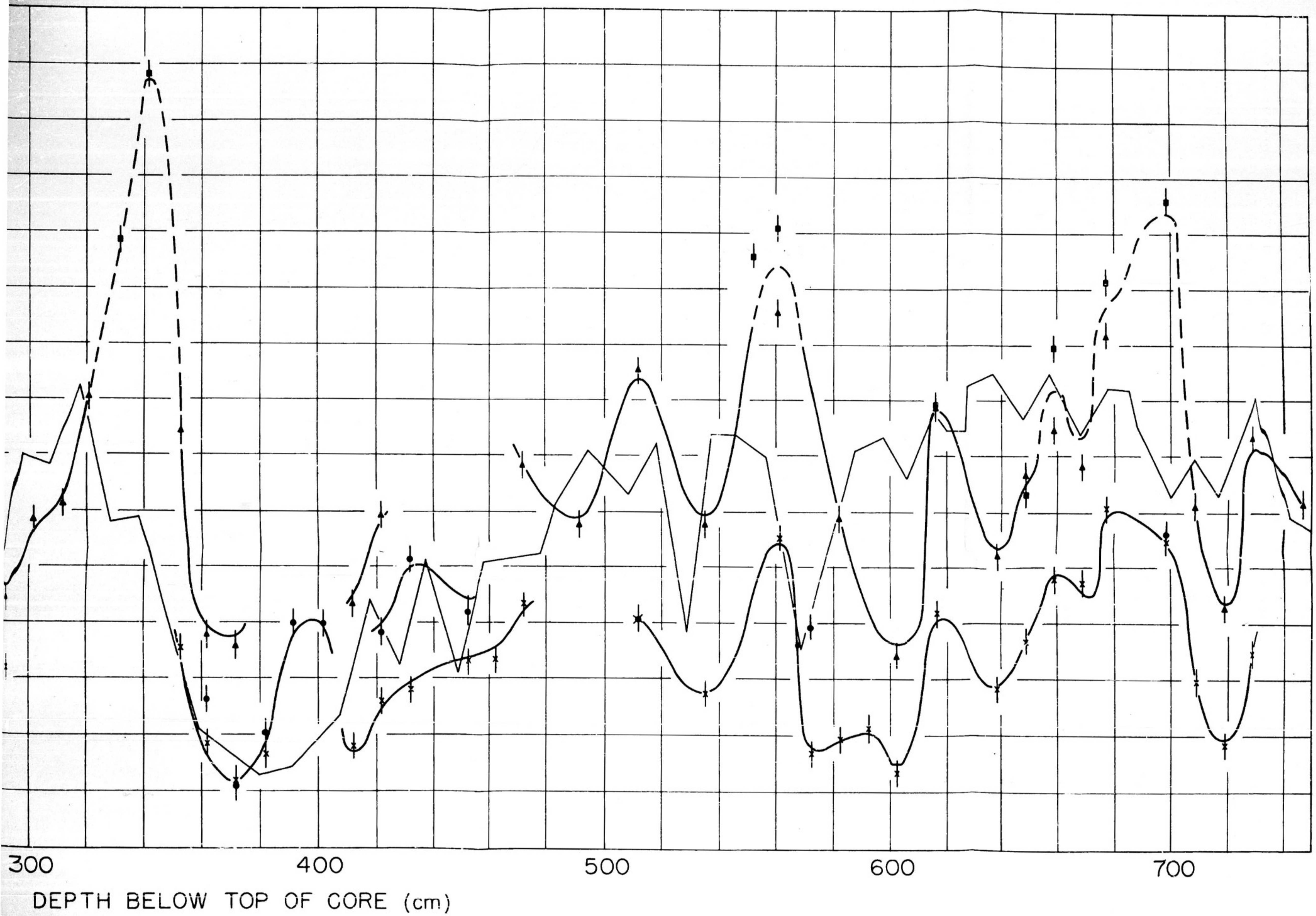
(685-2:61-167)

CORE 189

LAT. 33° 54' N, LONG 28° 29' E, DEPTH 2664 m



1


100
50
% WARM FORAMINIFERA (>150μ)
300
400
500
600
700
DEPTH BELOW TOP OF CORE (cm)

(685-I:61-166)

2

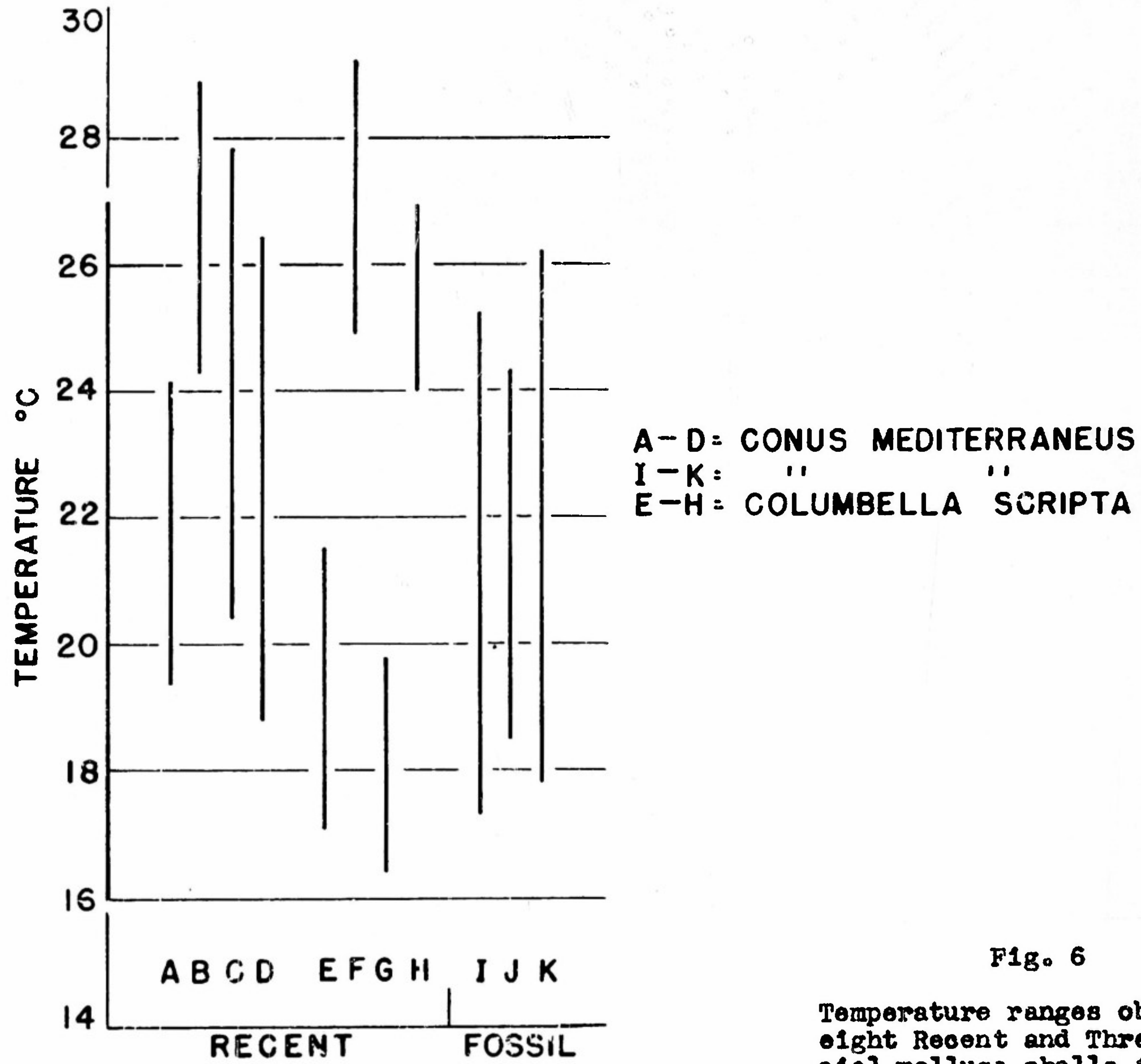


Fig. 6

Temperature ranges obtained from eight Recent and Three Postglacial mollusc shells from Kouali Point, Algeria. The thick line along the temperature scale represents the environmental temperature range.